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Evaluation of Different Carbon Monoxide Sensors for Battery Charging Stations

James H. Rowland[1], **Liming Yuan**[1], **Richard A. Thomas**[1], **Lihong Zhou**[1]

[1]Pittsburgh Mining Research Division, National Institute for Occupational Safety and Health, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA

Abstract

Hydrogen (H_2) gas released during battery charging can result in cross-interference for carbon monoxide (CO) sensors used for early fire detection and compromise the integrity of the mine atmospheric monitoring system (AMS). In this study, a series of laboratory-scale and full-scale experiments were conducted to evaluate the responses of different CO sensors to H_2 gas. In the laboratory-scale experiments, constant H_2 concentrations in the airflow, from 100 to 500 ppm, pass through sensors. While in the full-scale experiments, increasing H_2 concentrations generated as a byproduct from charging the batteries at the battery charging station rise to the sensors under different ventilation scenarios. The H_2 concentrations at the CO sensor location were measured using H_2 sensors and were correlated with the CO sensor response. The effects of ventilation and sensor location on the CO sensors responses were also analyzed. The results of this study can help mining companies to select appropriate CO sensors and improve the deployment of these sensors to ensure the safeguard of underground miners.

Keywords

Atmosphere monitoring system; Battery charging station; Carbon monoxide sensor

1 Introduction

As many types of battery-powered mining equipment such as scoops and shield haulers are used in underground mining operations, charging stations are required to charge the equipment batteries. These batteries are of lead acid chemistry. A safety issue exists with the battery charging stations as all lead acid batteries produce flammable H_2 gas during the normal charging process. Overcharging or excessive heat can quickly cause batteries to produce even more H_2. If H_2 is not appropriately diluted or dispersed, it builds up, and the risk of fire and explosion increases. Mine Safety and Health Administration (MSHA) regulation (30 CFR Part 75.340) [5] requires that battery charging stations should be housed

✉James H. Rowland, jlr5@cdc.gov.

Conflict of Interest The authors declare that there is no conflict of interest.

Compliance with Ethical Standards

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in noncombustible structures or be equipped with a fire suppression system. When a fire suppression system is used, the battery charging stations must be ventilated with intake air that is directed into a return air course or ventilated with intake air that is monitored for CO or smoke using an AMS. The monitoring of intake air ventilating battery charging stations should be done with sensors that are not affected by H_2.

MSHA reported in 2011 that most battery charging stations were not housed in noncombustible structures and, thus, must be protected by a fire suppression system [4]. In practice, CO sensors are often installed in underground battery charging station areas to detect an overheating or a fire through an AMS. Research has been conducted to examine the various types of fire sensors used for different AMSs in underground coal mines. Litton and Perera [3] conducted a series of experiments in NIOSH's Safety Research Coal Mine (SRCM) using fires of common mine combustible materials and for both flaming and non-flaming combustion to evaluate different sensors for mine fire detection used by AMSs. Rowland et al. [6] evaluated detection and response times of fire sensors using an AMS by conducting a series of full-scale fire experiments in the SRCM with fires of different combustible materials such as high- and low-volatility coals, conveyor belts, brattice materials, different types of wood, diesel fuel, and a foam sealant. The results showed that, through proper selection of sensors and their locations, a mine-wide AMS can provide sufficient early fire warning timing, thereby improving the health and safety of miners.

To ensure early detection of fires and reliable monitoring of intake air in battery charging station areas, it is imperative for CO sensors to function correctly. However, CO sensors used in underground mines are of the electrochemical type which can exhibit cross-interference with other gases. Electrochemical gas sensors are remarkably versatile as they are compact, require very little power, exhibit excellent linearity and repeatability, and generally have a long life span. Electrochemical sensors are fuel cell-like devices consisting of an anode, cathode, and electrolyte. The components of the cell are selected in such a way that the subject gas is allowed to diffuse into the cell, which causes chemical reactions and generates a current. As the diffusion of the gas into the cell is limited, so the rate of gas entering the cell is solely dependent on the gas concentration.

The current generated is proportional to the fractional volume of the gas. One of the chief limitations of electrochemical sensors is the effect of interfering gases on the sensor readings. For the electrochemical CO sensors, one interfering gas is H_2 which is always released during the normal battery charging process for lead acid batteries. The reason that CO sensors are potentially susceptible to H_2 interference is the reaction that is used to detect gas. Hydrogen is actually part of the detection reaction. To overcome this cross-interference, certain H_2-compensated CO sensors were developed that measure H_2 and subsequently subtract that value from the combined CO + H_2 reading. Another method of overcoming cross-interference is by using a catalyst system designed to limit the response of the sensor to H_2. However, the H_2-compensated CO sensors can only reduce the cross-interference to a certain extent, and some of these sensors may not function as well as expected. There is no information available about how well these CO sensors perform under different H_2 interference scenarios. In this study, a comprehensive evaluation of CO sensors for battery

charging stations was conducted to examine the responses of both normal CO sensors and H_2-compensated CO sensors to various H_2 concentrations.

2 Experimental Apparatus and Procedure

Both laboratory-scale and full-scale experiments were conducted to evaluate the performance of different CO sensors under H_2 cross-interference. Seven commonly used CO sensors from five different manufacturers were tested: Rel-Tek, AMR, Conspec, Pyott-Boone 1 (designated as PB 1), Pyott-Boone 2 (designated as PB 2), Strata 1, and Strata 2. All of these sensors are diffusion-type electrochemical sensors and their specifications are shown in Table 1. The Conspec H_2-compensated CO sensor uses the same sensor module as the AMR, so the Conspec H_2-compensated CO sensor was not tested in this study. All sensors are MSHA approved for use in underground coal mines and were calibrated before each test.

2.1 Laboratory-Scale Testing of CO Sensors

In the laboratory-scale experiments, a manifold was fabricated to connect all the CO sensors together, and all sensors were exposed to the same airflow simultaneously. The manifold was constructed using 0.5-in. and 0.25-in. copper tubing, connected to 0.25-in. Tygon tubing. The Tygon tubing was used to connect to each CO sensor separately, as shown in Fig. 1. The calibration gas cylinder was connected to the manifold at both ends using 0.5-in. Tygon tubing. A flow meter was used to measure the gas flow rate from the calibration gas cylinder. During the test, the calibration gas of different H_2 concentrations, 100, 200, and 500 ppm, was applied into both ends of the manifold for 8 min and 30 s at a flowrate of 500 mL/min until readouts were stable; then, the gas was shut off. A pinhole was placed into the tubing in front of each sensor to bleed off the pressure and gas. There was a 30-s delay before flowing gas to obtain a zero point. A data acquisition system was used to collect the data from each sensor during the test for further analysis.

2.2 Full-Scale Battery Charging Station Testing of CO Sensors

Full-scale experiments were conducted in a battery house that contains 48-cell, 96-V lead acid batteries and a charger, as shown in Fig. 2a. These batteries were previously used for an underground locomotive. There was a ventilation fan at the top side wall of the house and a louvered vent at the opposite top side wall to ventilate the battery house. The size of the ventilation fan was 20 in. × 20 in. with a 330 fpm airflow. The vent opening opposite to the ventilation fan was 21 in. × 14 in. All CO sensors were mounted on a frame 36 in. above the top of the batteries. Three H_2 sensors were installed above the batteries to measure the H_2 concentrations. One H_2 sensor was mounted at the same height as the CO sensors, 36 in., and the other two H_2 sensors were mounted at lower heights of 24 in. and 12 in., respectively.

To investigate the factors that may influence the H_2 dilution, a 50 in. × 38 in. × 48 in. plywood enclosure was built around the batteries, as shown in Fig. 2b. The plywood enclosure had a Plexiglas® front so that the sensor displays could be easily read. The top of the enclosure was covered with plastic, and the coverage was changed in the tests to examine

the effect of the top opening on the measured H_2 concentrations. The back of the battery enclosure was 80 in. from the ventilation fan, and the top of the battery enclosure was 19 in. lower than the center of the ventilation fan.

The batteries were discharged overnight with a load center to ensure that the batteries would require a full charge before each sensor test. Before starting the battery charger, the initial draw on the charger was 40 A. When the test was ended due to sensor saturation, the charger was usually at or lower than 20 A.

3 Experimental Results

3.1 Laboratory-Scale Testing

A total of 13 laboratory-scale CO sensor tests were conducted using different H_2 concentrations in the airflow. A sensor response test was first conducted without H_2 but with 25 ppm CO in the airflow to examine the sensor response to the standard CO calibration gas using the testing apparatus. Figure 3 shows the responses of the seven CO sensors. The Strata 1 sensor had the shortest response time, 30 s, while the PB 2 sensor had the longest response time of 120 s. The stable readings for all sensors after 10 min were not exactly 25 ppm. The lowest reading was about 20 ppm, while the highest reading was about 27 ppm. This is consistent with Edwards and Morrow's [2] finding that, in a static environment, the CO sensors consistently underestimated the gas concentration, with variation in the underestimation between 6 and 19%.

An "ideal" CO sensor would not be affected by exposure to H_2. Figures 4, 5, and 6 show the responses of CO sensors with the H_2 concentration in the airflow at 100, 200, and 500 ppm, respectively. With 100 ppm H_2 in the airflow, the PB 2 and Strata 1 sensors responded with elevated CO readings above 25 ppm, while the AMR sensor responded with the lowest CO reading of about 2 ppm. Other CO sensors' readings were between 2 and 25 ppm. As 10 ppm CO is commonly used as the threshold value for alarming in mine fire detection systems, this value is used as the criterion for determining if a CO sensor is impacted by H_2 to the extent that a false alarm occurs. With the 100 ppm H_2, three CO sensors were not impacted, two being H_2-compensated sensors. However, another H_2-compensated CO sensor, PB 1, was affected. With the H_2 concentration increased to 200 and 500 ppm in the airflow, the number of CO sensors not impacted decreased to 2 and 1, respectively. With the H_2 concentration at 500 ppm in the airflow, only the AMR sensor showed CO levels less than 10 ppm. Out of all sensors tested, the PB 2 and Strata 1 sensors always produced the highest CO response to the presence of H_2 in the airflow.

Figure 7 compares stable readings from all CO sensors with different H_2 concentrations in the airflow. Generally speaking, with the increase of H_2 concentration, the CO sensor reading also increased. Only readings from two Strata sensors exhibited a linear relationship with the H_2 concentration. Other sensor readings showed a higher rate of increase when H_2 concentration was increased from 200 to 500 ppm than when increased from 100 to 200 ppm.

Tests were also conducted to examine the effect of NO_2 on the CO sensor reading as diesel equipment are often used in the underground mines. Figure 8 shows CO readings with 50 ppm of NO_2 in the airflow. Only the Rel-Tek and Conspec sensors registered CO levels greater than 10 ppm. The PB 1 sensor produced a reading of 5 ppm, while other sensors reported no CO.

3.2 Full-Scale Battery Charging Station Testing

3.2.1 Effects of Battery Enclosure and Ventilation—A total of 11 full-scale tests of CO sensors were conducted using the battery charging station. As H_2 is released during charging, it rises and is removed by ventilation airflow. To investigate the environmental factors that affect H_2 dilution and removal after its release, the sealed battery enclosure was employed with the top opened at 44%, 72%, or 100%. The first experiment measured H_2 levels using the H_2 sensor for the various opening percentages (Fig. 9). Unlike laboratory-scale tests, H_2 concentrations measured from battery charging continually increased. With 44% of the enclosure top opened, H_2 concentration increased quickly, reaching 1000 ppm in over 20 min. With the enclosure top opening increased to 72 and 100%, the H_2 concentration increased more slowly, and the time for H_2 concentration to reach 1000 ppm increased to 118 min and 143 min, respectively.

CO sensors were then tested with the enclosure top 100% open. The CO sensor readings under this condition are shown in Fig. 10. As in the laboratory-scale sensor tests, the PB 2 and Strata 1 sensors produced the highest CO readings. All CO sensors were affected by the presence of H_2 except the AMR sensor, which was consistent with the results of the laboratory-scale test using 500 ppm H_2 in the airflow.

To mimic complex underground conditions where ventilation flow may be restricted, the effect of ventilation on the H_2 concentration was investigated with or without the sealed enclosure. Obviously, the worst case scenario is with the sealed enclosure and no ventilation. The top of the enclosure was 100% open thereafter. Figure 11 shows the effect of the enclosure on the measured H_2 concentrations with no ventilation. There was no significant difference between H_2 concentrations with and without the enclosure, indicating that without the ventilation, the effect of the enclosure on the H_2 concentration is insignificant. With the enclosure in place, the H_2 concentration increased approximately linearly with the time. Without the enclosure, the H_2 concentration increased at a faster rate at the beginning and at a slower rate later in the test. Without the enclosure, there was more fluctuation in the measured H_2 concentration, and it took longer for the H_2 concentration to reach 1000 ppm.

Figure 12 shows the effect of the enclosure on the measured H_2 concentrations at 36-in. position with the ventilation on. With the enclosure, the H_2 concentration increased quickly, reaching 1000 ppm in 3 h. As the enclosure was preventing air flow from outside into the enclosure, the ventilation caused more fluctuation in the measured H_2 concentration. Without the enclosure, the H_2 concentration increased more slowly and reached 450 ppm in about 6 h as ventilation dispersed the gas quickly, indicating the significant effect of the ventilation on the H_2 concentration.

CO sensors were then tested without the enclosure and with the ventilation on as this is the case that is more likely to occur in an underground mine. The readings of the CO sensors under these conditions are shown in Fig. 13. The PB 2 sensor still produced the highest reading, 70 ppm in 6 h. Three CO sensors showed readings less than 10 ppm after 6 h: AMR, Strata 2, and PB 1, all being H_2-compensated CO sensors.

3.2.2 Effect of Sensor Location—Tests were also conducted to study the effect of CO sensor location on the sensor responses. In one test, all sensors were mounted 64 in. above the top of the batteries, as compared to 36 in. in the previous tests. In another test, all sensors were mounted 70 in. above the top of the batteries and 22 in. in front of the exhaust fan, as compared to 105 in. in the previous tests. In the latter test, the sensors were in direct alignment with the exhaust fan. Figure 14 shows measured H_2 concentrations in three tests with the sensors mounted 36, 64, and 70 in. above the top of batteries. The data from the test with 70-in. sensor height are only good for the first 215 min due to an unplanned experimental condition change. As the height of the sensors increased, H_2 concentration was slightly lower at the beginning, but increased after 3 h and reached 700 ppm in 5 h. Due to a stronger ventilation airflow at the 64-in. location, the H_2 concentration fluctuated more compared to the 36-in. sensor location.

Figure 15 shows CO sensor responses at the height of 64 in. above the batteries. After about 4 h, CO sensor readings fluctuated. The PB1, PB 2, Conspec, and Rel-Tek sensors showed CO readings in excess of 10 ppm, while the AMR, Strata 1, and Strata 2 sensors were below this level. Figure 16 shows CO sensor responses at the height of 72 in. above the batteries. After about 4 h, only the AMR and Rel-Tek sensors showed responses less than 10 ppm.

4 Discussion

In this study, laboratory-scale tests were conducted in a static environment, while full-scale battery charging station tests were conducted in dynamic environments, closer to real-mine environments for battery charging stations. The laboratory-scale test results indicate that at 100 ppm H_2, three sensors—the Conspec, Strata 2, and AMR—showed readings less than 10 ppm, an alarm threshold in mine fire detection systems. At 200 ppm H_2, two sensors—the Conspec and AMR—produced readings less than 10 ppm, and at 500 ppm, only the AMR sensor exhibited this behavior.

In full-scale tests without any ventilation, only the AMR sensor showed readings less than the threshold. This was consistent with the laboratory-scale test result at 500 ppm H_2 concentration. In the full-scale tests with the ventilation, three sensors—the PB1, Strata 2, and AMR—showed readings less than the alarm threshold. Sensor performance also varied with height above the recharging batteries and distance from the fan. In the test with 64-in. sensor height, three CO sensors—the Strata 1, Strata 2, and AMR—showed minimal cross-interference. In the test with 22-in. distance from the fan, two sensors—the Rel-Tek and AMR—showed similar behavior. Only the AMR sensor was minimally impacted in all test scenarios.

It should be noted that there was a clear trend for the performance of each sensor in the laboratory-scale tests when the H_2 concentration in the airflow was increased from 100 to 200 ppm, and then to 500 ppm, as those were well-controlled static tests with a unidirectional airflow. However, there was not a clear trend for the performance of each sensor in the full-scale battery charging station tests, except for the AMR sensor. As these were the dynamic tests, the H_2 concentration at each CO sensor location was affected by the ventilation and the sensor height. The ventilation airflow not only affected the H_2 concentration at the CO sensor location, but also affected the response of the CO sensor itself as the CO sensors are the diffusion-type electrochemical sensors. Edwards and Friel [1] conducted an in-mine evaluation of CO and smoke detectors and found that the diffusion-mode CO sensor had an over 25% lower reading than the mechanical-pump-mode CO sensor. The high readings of the PB 1 and Strata 1 sensors in the test close to the fan (Fig. 16) are likely attributed to the influence of the ventilation airflow.

5 Summary

Battery charging processes liberate hydrogen gas that affect normal operation of CO sensors. Laboratory-scale and full-scale experiments were conducted to evaluate the responses of different CO sensors when exposed to H_2. These analyses assumed a 10-ppm alarm level for CO, where any CO sensor response to H_2 gas in excess of that would trigger a false alarm. The experimental results indicate that out of the seven CO sensors tested, only the AMR sensor was minimally affected in all laboratory-scale and full-scale tests. Except for the AMR sensor, the other two H_2-compensated CO sensors, the PB 1 and Strata 2, did not perform any better than non-H_2-compensated CO sensors.

In the laboratory-scale tests, the Conspec sensor performed well in H_2 concentrations up to 200 ppm. In full-scale testing, the cross-interference from H_2 was also affected by the ventilation airflow and the sensor location as this airflow could affect both H_2 concentration and CO sensor response. Two CO sensors, the Rel-Tek and Conspec, also experienced cross-interference effects with exposures to NO_2, producing responses in excess of 10 ppm.

The actual quantities of H_2 released from the battery charging may vary greatly from battery to battery. The H_2 concentration in the vicinity of the batteries can be affected by the ventilation. In this study, H_2 concentrations exceeded 1000 ppm when the batteries were not ventilated. With ventilation applied, the H_2 concentration reached about 450 ppm. To overcome the cross-interference from H_2, it is important to select appropriate CO sensors minimally affected by the presence of H_2, and provide ventilation to dilute and remove accumulations of this gas to prevent false alarms and ensure the effectiveness of fire detection system for the battery charging stations. The experimental results of this study may help underground mine operators to better select and deploy CO sensors for the underground battery changing stations to reduce occurrences of fatal fires and explosions due to accumulation of combustible gases.

Acknowledgements

The authors wish to thank John Soles of Pittsburgh Mining Research Division (PMRD) for conducting the laboratory-scale and full-scale sensor tests.

References

1. Edwards JC, Friel GF (1996) Comparative in-mine evaluation of carbon monoxide and smoke detectors, Bureau of Mines Report of Investigations 9622, 1–11
2. Edwards JC, Morrow GS (1994) Evaluation of the response of diffusion-type carbon monoxide sensors. Bureau of Mines Report of Investigations 9520, 1–8
3. Litton C, Perera IE (2015) Evaluation of sensors for mine fire detection using an atmospheric monitoring system. Min Eng 67(6):68–75
4. Mine Safety and Health Administration (MSHA) (2011) Fire suppression systems used to protect battery charging stations and other unattended electrically powered equipment in underground coal mines. Program Information Bulletin No P11–22
5. Mine Safety and Health Administration (MSHA) (2016) Title 30 Code of Regulations (30 CFR), Part 75.340
6. Rowland JH, Litton CD, Thomas RA (2016) Evaluation of detection and response times of fire sensors using an atmosphere monitoring system. Trans Soc Min Metall Explor Inc 340:104–112 [PubMed: 28529442]

Fig. 1.
Laboratory-scale CO sensor testing apparatus

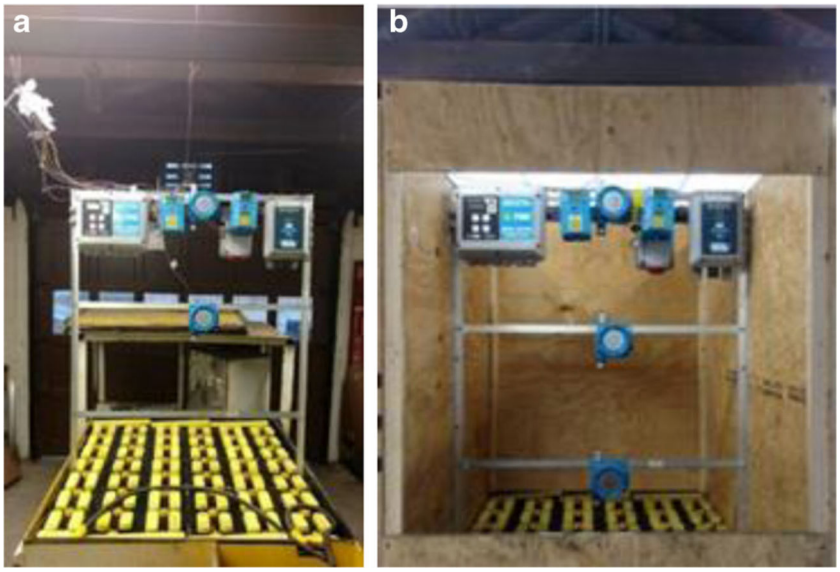

Fig. 2.

Full-scale CO sensor testing apparatus with the battery charging stations: **a** without the enclosure; **b** with the enclosure

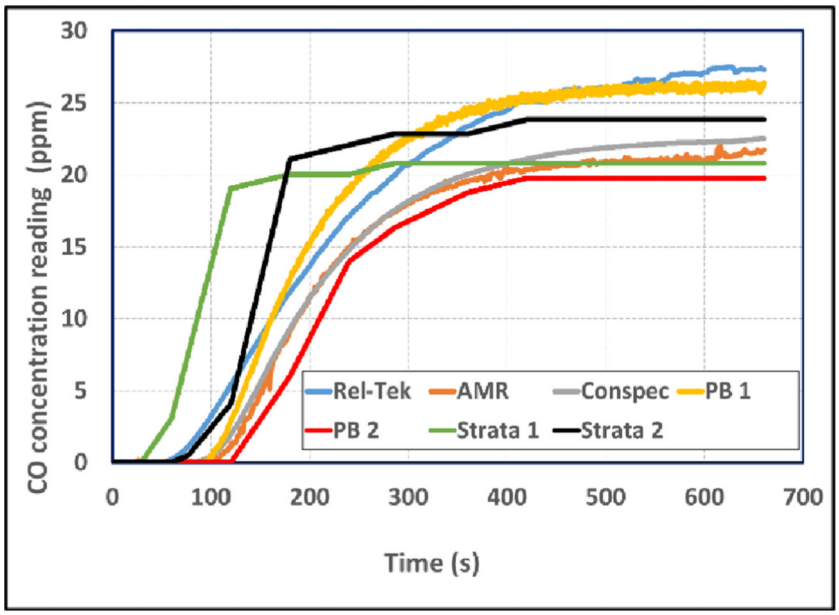

Fig. 3.
CO sensor responses with 25 ppm CO in airflow

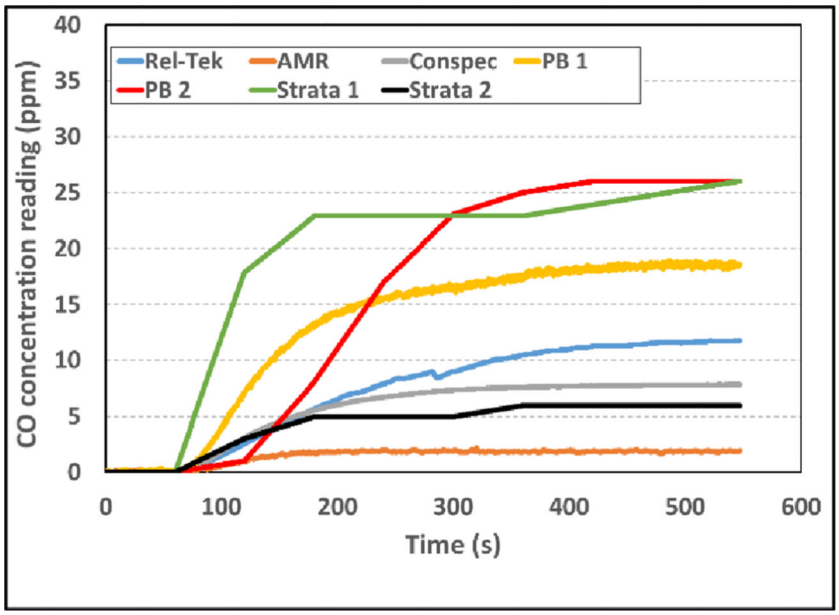

Fig. 4.
CO sensor responses with 100 ppm H_2 in airflow

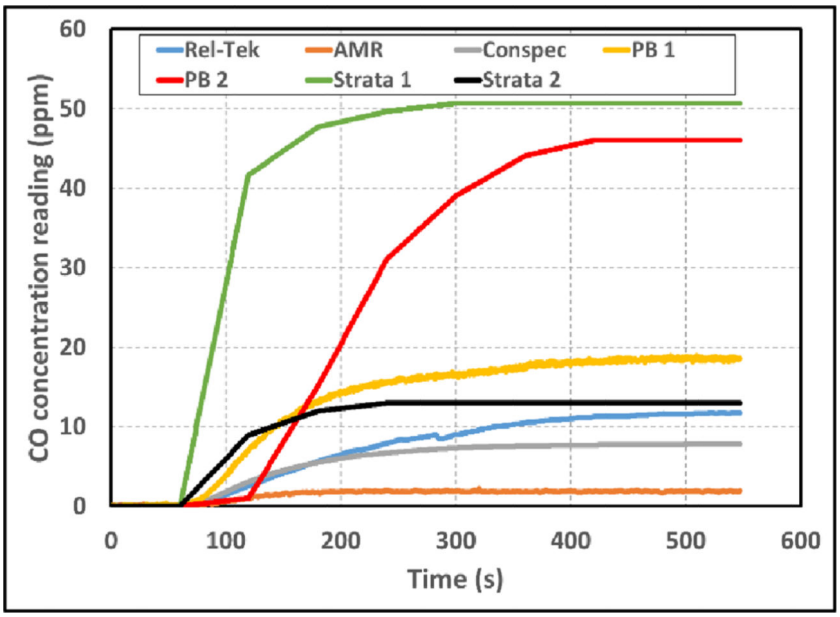

Fig. 5.
CO sensor responses with 200 ppm H_2 in airflow

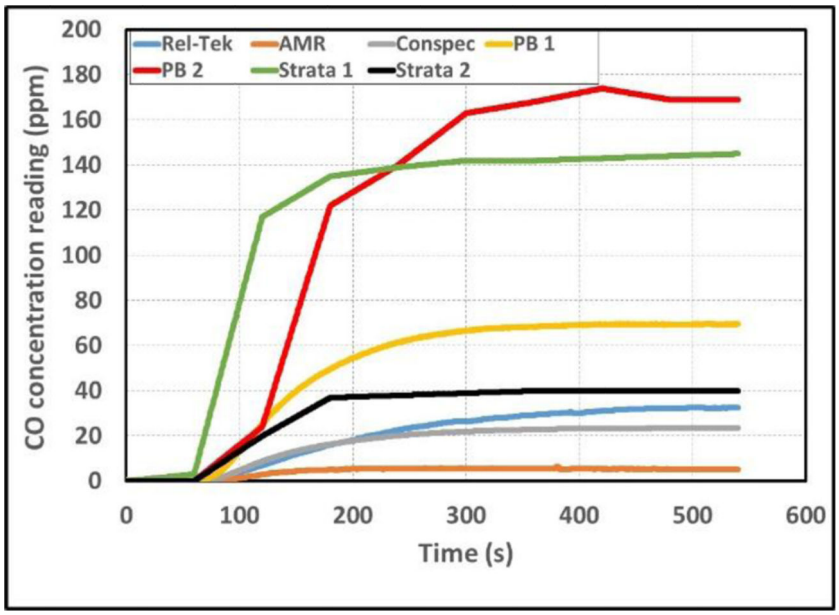

Fig. 6.
CO sensor responses with 500 ppm H_2 in airflow

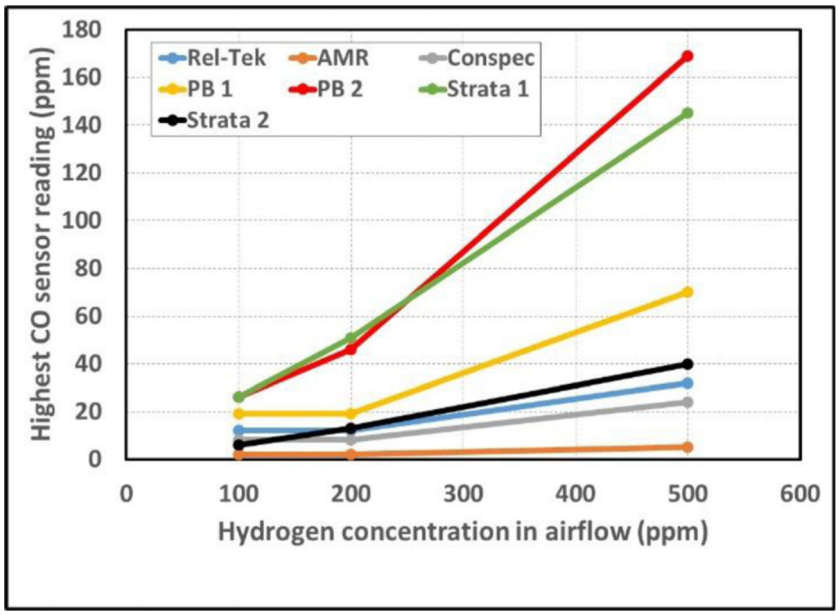

Fig. 7.
Comparison of CO sensor readings with different H_2 concentrations

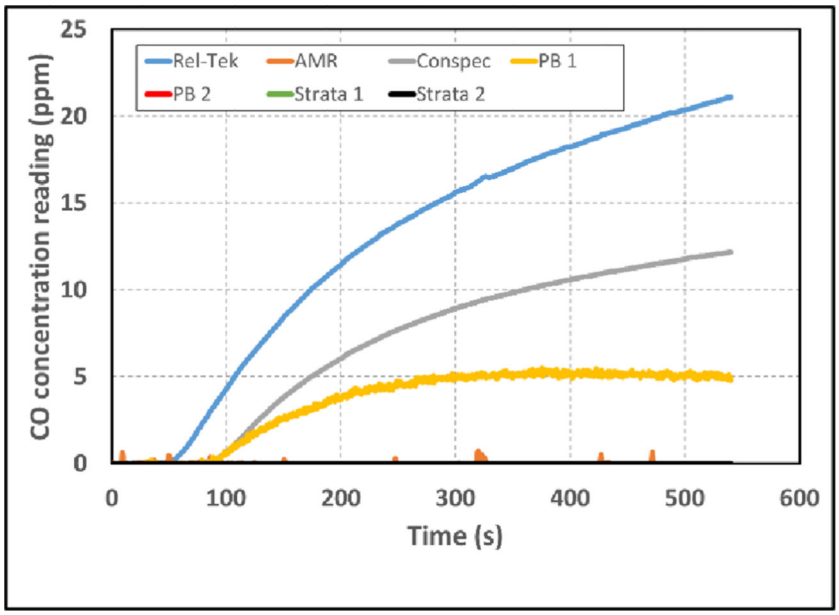

Fig. 8.
CO sensor responses with 50 ppm NO_2 In airflow

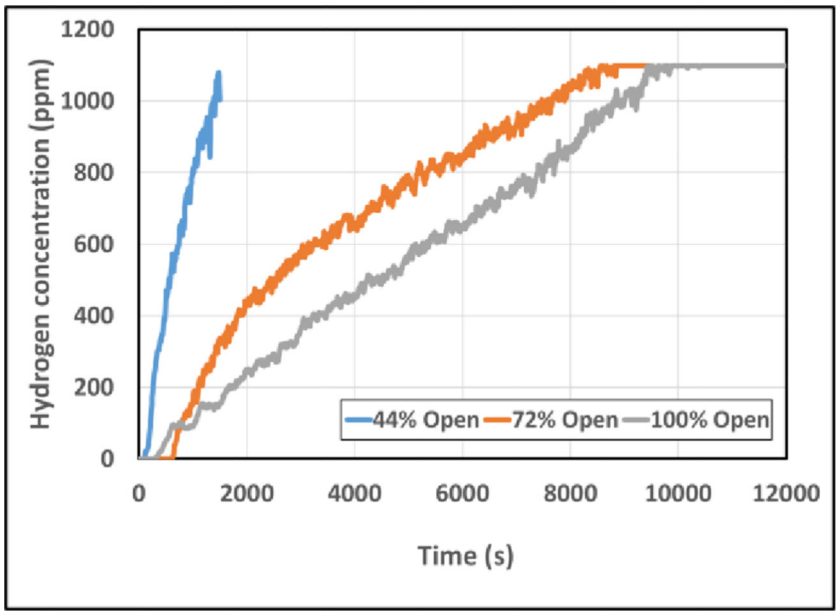

Fig. 9.

H_2 concentrations with different percentage top opening

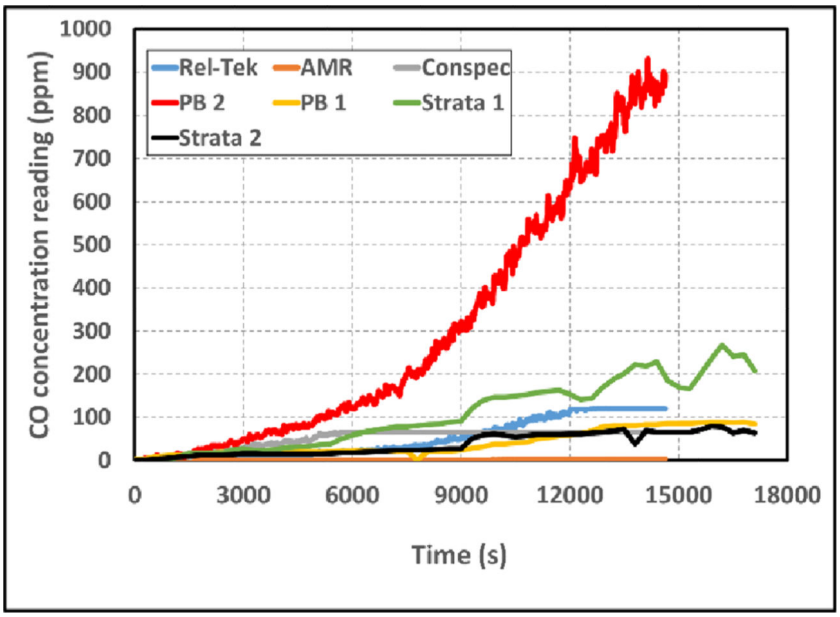

Fig. 10.
CO sensor responses with full top opening

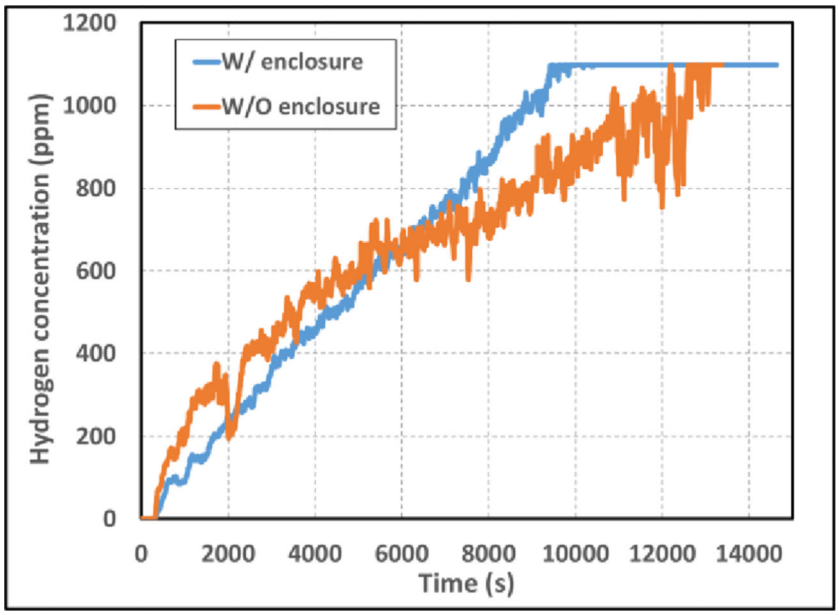

Fig. 11.
Effect of the enclosure on H_2 concentrations: without ventilation

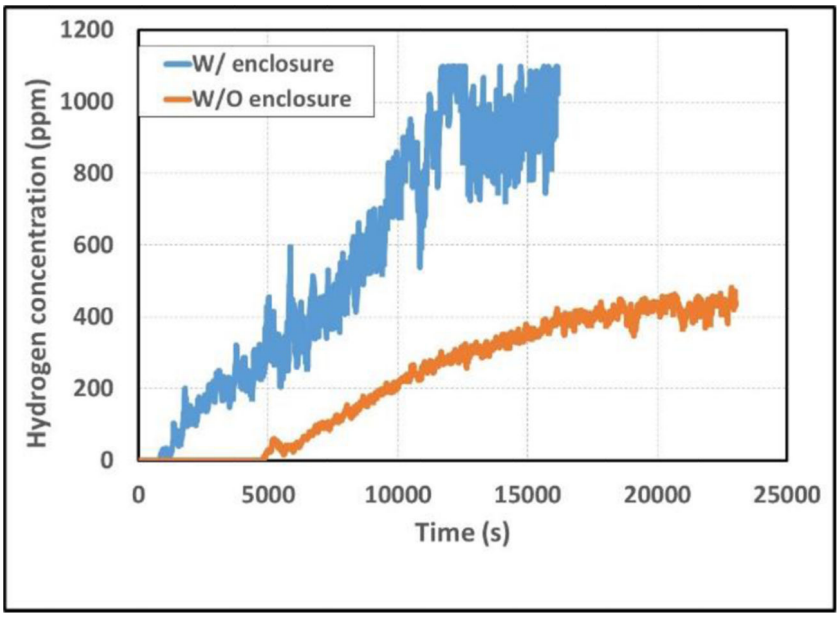

Fig. 12.
Effect of the enclosure on H_2 concentrations: with ventilation

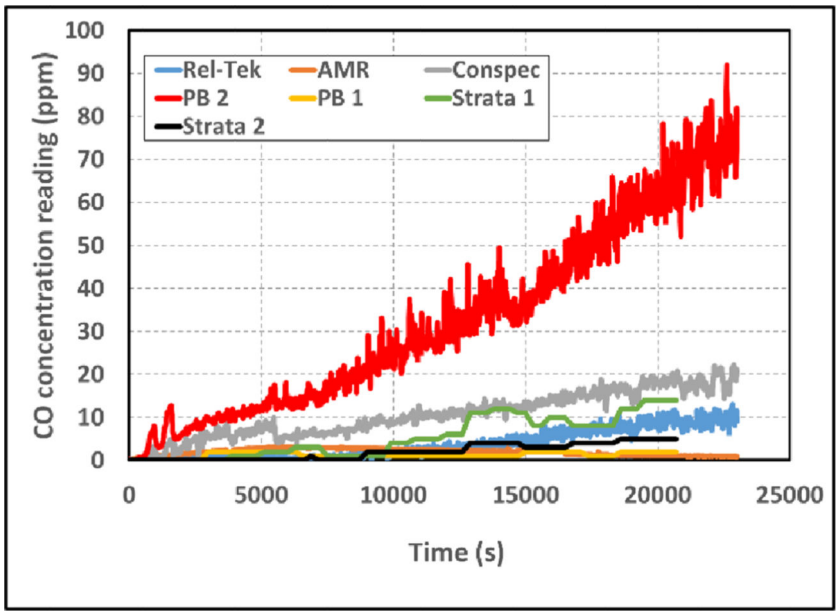

Fig. 13.
CO sensor responses without the enclosure and with ventilation

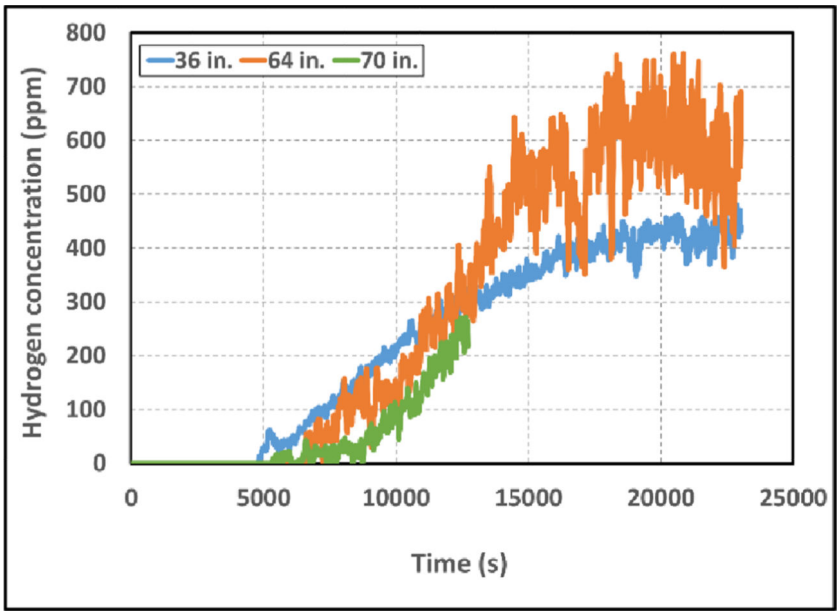

Fig. 14.
Effect of sensor location on H_2 concentrations

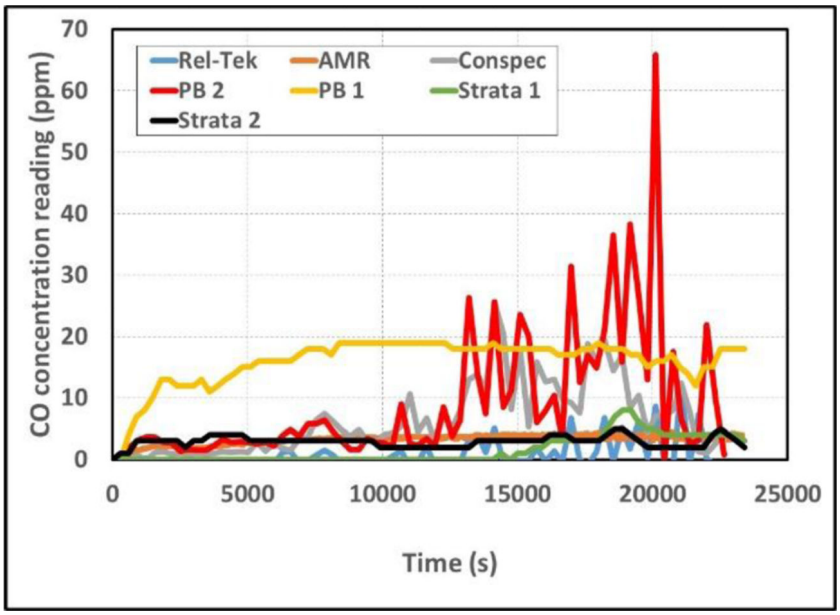

Fig. 15.
CO sensor responses with sensors at 64-in. height

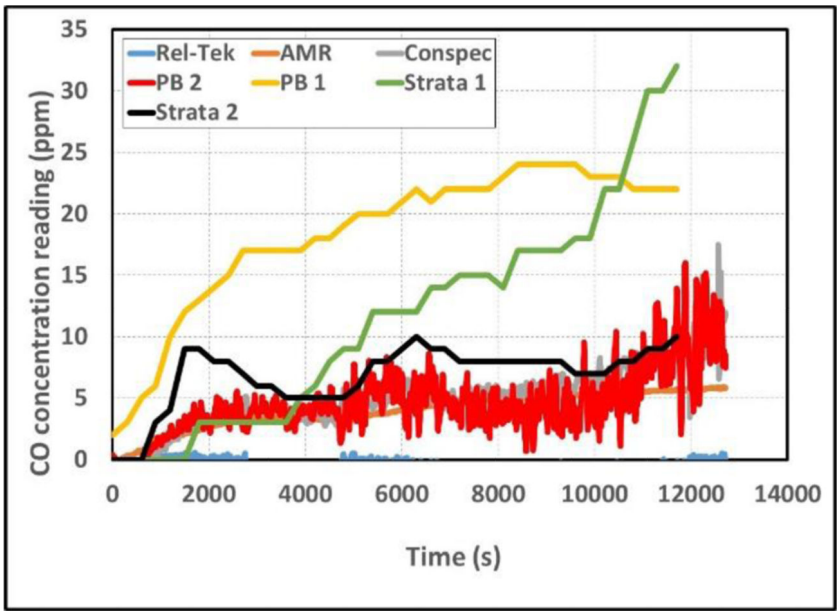

Fig. 16.
CO sensor responses with sensors at 70-in. height

Table 1

CO sensor specifications

Manufacturer	Range (ppm)	H_2-compensated
AMR	0–2000	Yes
Conspec	0–2000	No
Pyott-Boone 1 (PB1)	0–1000	Yes
Pyott-Boone 2 (PB2)	0–200	No
Rel-Tek	0–100	No
Strata 1	0–5000	No
Strata 2	0–2000	Yes